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PROVISIONAL APPLICATION COVER SHEET

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This is a request for filing a PROVISIONAL APPLICATION under 37 CFR 1.53(c).

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TITLE OF INVENTION (280 characters max)

MULTIFOCAL OPHTHALMIC LENS

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ENCLOSED APPLICATION PARTS (check all that apply)

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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

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Respectfully submitted,

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Niki Dillingham

851099v1

Multifocal ophthalmic lens

TECHNICAL FIELD OF THE INVENTION

The present invention relates to a multifocal ophthalmic lens, and more in detail to a multifocal intraocular lens with reduced aberrations.

TECHNICAL BACKGROUND

Generally, a multifocal lens is required to provide a certain power for far vision and different, usually greater (more positive), powers for mid and near vision, the additional power for mid and near vision sometimes being referred to as "mid-add" and "near-add", which is usually expressed in dioptres. Multifocal lenses with two foci are referred to as bifocal.

Compared with monofocal ophthalmic lenses, multifocal ophthalmic lenses offer the advantage of reduced spectacle dependency, whereas patients with monofocal lenses generally need reading spectacles. In an ideal situation, the patient will have good vision in distance and near, while the depth of focus will enable vision in the intermediate. In this situation, the patient doesn't need spectacles in any situation. However, since a multifocal lens splits the available light into two or more foci, the visual quality in each focus is somewhat reduced. When a distant object is focused on the retina, a blurred image is superimposed due to the presence of the additional foci and vice versa, which obviously reduces the image quality. The reduced visual quality can be divided in reduced contrast sensitivity and appearance of optical phenomena, like straylight and halos. Moreover a patient has to undergo a learning period after implantation, as the two (or more) simultaneous images displayed on the retina can be confusing in the beginning. In most cases, the blurred image is discarded by the human visual perception and retinal processing system.

Usually, multifocal lenses are designed according to one or more of the following optical principles:

1. Diffractive type: conventional refractive lens combined with diffractive optics that splits light into two or more focal points.

2. Refractive optics with annular zones/rings with different radii of curvatures.

Examples of bifocal and multifocal intraocular lenses are disclosed in US 4,642,112 and US 5,089,024. Examples of commercially available multifocal lenses are: model CeeOn® model 811 E, Pharmacia, Kalamazoo, MI and SA 40, AMO, Irvine, CA. The former is based on diffractive optics, whereby light is partitioned into two focal points, one for distance vision and one for near vision. The latter is a distance-dominant, zonal-progressive, multifocal optic with a 3.5-diopter near-add

After IOL implantation, any remaining defocus (sphere) and astigmatism (cylinder) can be corrected by spectacles or contact lenses. Beside first order defocus and astigmatism of the eye a number of other vision defects could be present. For example aberrations of different orders occur when a wavefront passes a refracting surface. The wavefront itself becomes aspheric when it passes an optical surface that has imperfections, and vision defects occur when an aspheric wavefront falls on the retina. Both the cornea and the lens in the capsular bag contribute thus to these types of vision defects if they deviate from being perfect or perfectly compensating optical elements. The term aspheric will in this text include both asphericity and asymmetry. An aspheric surface could be either a rotationally symmetric or a rotationally asymmetric surface and/or an irregular surface, i.e. all surfaces not being spherical.

Recently, in studies on older subjects, it has been discovered that the visual quality of eyes having an implanted monofocal IOL, having spherical lens surfaces (hereafter referred to as a conventional intraocular lens (CIOL)) is comparable with normal eyes in a population of the same age. Consequently, a 70 year old cataract patient can only expect to obtain the visual quality of a non-cataracteous person of the same age after surgical implantation of an intraocular lens, although such lenses objectively have been regarded as optically superior to the natural crystalline lens. This result is explained by the fact that CIOLs are not adapted to,

compensate for defects of the optical system of the human eye, namely optical aberrations.

In order to improve the performance of implanted intraocular lenses, efforts have been made to provide intraocular lenses for implantation that at least partly compensates for such aberrations (Reduced Aberration IOL, or RAIOL). The applicants own application WO 01/89424 discloses an ophthalmic lens providing the eye with reduced aberrations, and a method of obtaining such. The method comprises the steps of characterizing at least one corneal surface as a mathematical model, calculating the resulting aberrations of said corneal surface(s) by employing said mathematical model, selecting the optical power of the intraocular lens. From this information, an ophthalmic lens is modeled so a wavefront arriving from an optical system comprising said lens and corneal model obtains reduced aberrations in the eye. The ophthalmic lenses as obtained by the methods are thus capable of reducing aberrations of the eye.

Of current multifocal lenses, the optical quality is lower than for current monofocal lenses. This shows in contrast sensitivity measurements on pseudophakic patients. As the visual quality of multifocal lenses is relatively low, even minor improvements in optical quality will lead to visible improvements.

Both WO 00/76426 and US 6,457,826 mentions the possibility to make an aspheric BIOL. WO 00/76426 does not disclose use of any specific aspheric characteristic in the lens, but just mentions the possibility to combine an asphere with a diffractive pattern. However, US 6,457,826 states that optical corrections can be made by aspherizing an IOL surface, but it is not at all described how this could be done.

In view of the foregoing, it is therefore apparent that there is a need for multifocal ophthalmic lenses that are better adapted to compensate the aberrations caused by the individual surfaces of the eye, such as the corneal surfaces, and capable of better correcting aberrations other than defocus and astigmatism, as is provided with conventional multifocal intraocular lenses.

SUMMARY OF THE INVENTION

The object of the invention is to provide a multifocal intraocular lens and a method of designing for designing such, which overcome the drawbacks of the prior art devices and methods. This is achieved by the method as defined in claims 1, 40 and 81, and by the multifocal ophthalmic lens as defined in claims 102, 103 and 146.

One advantage with the multifocal intraocular lens according to the present invention is the improved visual quality that can be obtained.

Embodiments of the invention are defined in the dependent claims.

SHORT DESCRIPTION OF THE FIGURES

Fig. 1shows a calculated Modulation Transfer Function for a bifocal intraocular lens according to the present invention and a conventional bifocal lens.

Fig 2. shows a measured Modulation Transfer Function for a bifocal intraocular lens according to the present invention and a conventional bifocal lens.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The present invention generally relates to a multifocal ophthalmic lens and to methods of obtaining said multifocal intraocular lens that is capable of reducing the aberrations of the eye for at least one focus. By aberrations in this context is meant wavefront aberrations. This is based on the understanding that a converging wavefront must be perfectly spherical to form a point image, i.e. if a perfect image shall be formed on the retina of the eye, the wavefront having passed the optical surfaces of the eye, such as the cornea and a natural or artificial lens, must be perfectly spherical. An aberrated image will be formed if the wavefront deviates from being spherical. In this context the term nonspherical surface will refer to rotationally symmetric, asymmetric and/or irregular surfaces, i.e. all surfaces differing from a sphere. The wavefront aberrations can be expressed in mathematical terms in accordance with different approximate models as is explained in textbook references, such as M.R. Freeman, Optics, Tenth Edition, 1990.

In a first embodiment, the present invention is directed to a method of designing a multifocal ophthalmic lens with one base focus and at least one additional focus capable of reducing aberrations of the eye for at least one of the foci after its implantation. The base focus may also be referred to as far field focus and the at least one additional focus, as near field focus and mid field focus. The method comprises a first step of characterizing at least one corneal surface as a mathematical model, a second step wherein the mathematical model is employed for calculating the resulting aberrations of the corneal surface. An expression of the corneal aberrations is thereby obtained, i.e. the wavefront aberrations of a spherical wavefront having passed such a corneal surface. Dependent on the selected mathematical model different routes to calculate the corneal aberrations can be taken. The corneal surfaces are preferably characterized as mathematical models and the resulting aberrations of the corneal surfaces are calculated by employing the mathematical models and raytracing techniques. An expression of the corneal wavefront aberrations is thereby obtained, i.e. the wavefront aberrations of a wavefront having passed such a corneal surface. Dependent on the selected mathematical model different routes to calculate the corneal wavefront aberrations can be taken. Preferably, the corneal surfaces are characterized as mathematical models in terms of a conoid of rotation or in terms of polynomials or a combination thereof. More preferably, the corneal surfaces are characterized in terms of linear combinations of polynomials.

From the information of steps above an ophthalmic lens is modeled, such that a wavefront from an optical system comprising said lens and corneal model obtains reduced aberrations. The optical system considered when modeling the lens typically includes the cornea and said lens, but in the specific case it can also include other optical elements including the lenses of spectacles, or an artificial correction lens, such as a contact lens, a corneal inlay implant or an implantable correction lens depending on the individual situation.

Furthermore the base power for far vision, the light distribution between the at least two foci, and the optical power(s) for the additional focus/foci, of the ophthalmic lens has to be selected, which is done according to conventional methods for the specific need of optical correction of the eye, for example the method described in US Patent No. 5,968,095.

Modeling the multifocal lens involves selection of one or several lens parameters in a system which contributes to determine the lens shape for given, pre-selected refractive powers. This typically involves the selection of conventional lens parameters such as the anterior radius and surface shape, posterior radius and surface shape, the lens thickness and the refractive index of the lens, as well as parameters specific for multifocal lenses. As mentioned above there are a number of different ways by which to multifocal lenses may be designed. Hence, the multifocal specific parameters depend on what multifocal design that is used.

The multifocal ophthalmic lens according to the present invention can be realized in the form of a multifocal contact lens, a multifocal corneal inlay for aphakic patients, or the like, but it will be described in detail in the form of a multifocal intraocular lens. Furthermore the multifocal specific parameters discussed will be limited to parameters applicable on bifocal lenses of diffractive type, but it should be understood that the multifocal lens modeled according to present invention can be of any multifocal type or combinations thereof. A bifocal diffractive lens is a combination of a conventional refractive lens and a diffractive lens, the former focused to infinity and the latter for near vision. A diffractive lens consists of a series of radial rings or "zones" of decreasing width. Typically, the light distribution of a bifocal diffractive lens is set at around 50:50%, thus both the near and the far foci are accommodated. The diffractive lens may be formed on the anterior or posterior surface of the conventional lens, or at an intermediate position. The light distribution of the diffractive bifocal lens is determined by the step height of the diffractive zones. The power add for near field focus is determined by the diameters of the diffractive zones. Theoretically, this is independent of the refractive indices of the lens and the surrounding medium.

In practical terms, the lens modeling can be performed with data based on a conventional bifocal lens, such as the CeeOn® 811E lens from Pharmacia Corp. Values of the central radii of the lens, its thickness and refractive index are maintained, while selecting a different shape of the anterior and/or posterior surface, thus providing one or both of these surfaces to have a nonspherical shape.

According to one embodiment of the present invention, the anterior and/or posterior surface of the bifocal intraocular lens is modeled by selecting a suitable aspheric component.

Preferably the lens has at least one surface described as a nonsphere or other conoid of rotation. Designing nonspherical surfaces of lenses is a well-known technique and can be performed according to different principles and the description of such surfaces is explained in more detail in our PCT patent application WO 01/62188, to which is given reference.

The inventive method can be further developed by comparing wavefront aberrations of an optical system comprising the lens and the model of the average cornea with the wavefront aberrations of the average cornea and evaluating if a sufficient reduction in wavefront aberrations is obtained for at least one of the foci. Suitable variable parameters are found among the above-mentioned physical parameters of the lens, which can be altered so as to find a lens model, which deviates sufficiently from being a spherical lens to compensate for the corneal aberrations.

The characterization of at least one corneal surface as a mathematical model and thereby establishing a corneal model expressing the corneal wavefront aberrations is preferably performed by direct corneal surface measurements according to well-known topographical measurement methods which serve to express the surface irregularities of the cornea in a quantifiable model that can be used with the inventive method. Corneal measurements for this purpose can be performed by the ORBSCAN® videokeratograph, as available from Orbtech, or by corneal topography methods, such as EyeSys® from Premier Laser Systems. Preferably, at least the front corneal surface is measured and more preferably both front and rear corneal surfaces are measured and characterized and expressed together in resulting wavefront aberration terms, such as a linear combination of polynomials which represent the total corneal wavefront aberrations. According to one important aspect of the present invention, characterization of corneas is conducted on a selected population with the purpose of expressing an average of corneal wavefront aberrations and designing a lens from such averaged aberrations. Average corneal wavefront aberration terms of the population can then be calculated, for example as an average linear combination of polynomials and used in the lens design method. This aspect includes selecting different relevant populations, for example in age groups, to generate suitable average corneal surfaces. Advantageously, lenses can thereby be provided which are adapted to an average cornea of a population relevant for an individual elected to undergo cataract surgery or refractive correction surgery including

implantation of an IOL or corneal inlays or phakic IOLs. The patient will thereby obtain a bifocal lens that gives the eye substantially less aberrations when compared to a conventional spherical lens.

Preferably, the mentioned corneal measurements also include the measurement of the corneal refractive power. The power of the cornea and the axial eye length are typically considered for the selection of the lens power in the inventive design method.

Also preferably, the wavefront aberrations herein are expressed as a linear combination of polynomials and the optical system comprising the corneal model and modeled intraocular lens provides, for at least one of the foci and preferably for each foci, a wavefront having obtained a substantial reduction in aberrations, as expressed by one or more such polynomial terms. In the art of optics, several types of polynomials are available to skilled persons for describing aberrations. Suitably, the polynomials are Seidel or Zernike polynomials. According to the present invention Zernike polynomials preferably are employed.

The technique of employing Zernike terms to describe wavefront aberrations originating from optical surfaces deviating from being perfectly spherical is a state of the art technique and can be employed for example with a Hartmann-Shack sensor as outlined in J. Opt. Soc. Am., 1994, Vol. 11(7), pp. 1949-57. It is also well established among optical practitioners that the different Zernike terms signify different aberration phenomena including defocus, astigmatism, coma and spherical aberration up to higher aberrations. In an embodiment of the present method, the corneal surface measurement results in that a corneal surface is expressed as a linear combination of the first 15 Zernike polynomials. By means of a raytracing method, the Zernike description can be transformed to a resulting wavefront (as described in Equation (1)), wherein Z_i is the i-th Zernike term and a_i is the weighting coefficient for this term. Zernike polynomials are a set of complete orthogonal polynomials defined on a unit circle. Below, Table 1 shows the first 15 Zernike terms and the aberrations each term signifies.

$$z(\rho,\theta) = \sum_{i=1}^{15} a_i Z_i \qquad (1)$$

In equation (1), ρ and θ represent the normalized radius and the azimuth angle, respectively.

Table 1

i	$Z_i(\rho,\theta)$	
1	1	Piston
2	$2\rho\cos\theta$	Tilt x
3	$2\rho\sin\theta$	Tilt y
4	$\sqrt{3}(2\rho^2-1)$	Defocus
5	$\sqrt{6}(\rho^2\sin 2\theta)$	Astigmatism 1st order (45°)
6	$\sqrt{6}(\rho^2\cos 2\theta)$	Astigmatism 1st order (0°)
7	$\sqrt{8}(3\rho^3-2\rho)\sin\theta$	Coma y
8	$\sqrt{8}(3\rho^3-2\rho)\cos\theta$	Coma x
9	$\sqrt{8}(\rho^3\sin 3\theta)$	Trifoil 30°
10	$\sqrt{8}(\rho^3\cos 3\theta)$	Trifoil 0°
11	$\sqrt{5}(6\rho^4-6\rho^2+1)$	Spherical aberration
12	$\sqrt{10}(4\rho^4-3\rho^2)\cos 2\theta$	Astigmatism 2nd order (0°)
13	$\sqrt{10}(4\rho^4-3\rho^2)\sin 2\theta$	Astigmatism 2nd order (45°)
14	$\sqrt{10}(\rho^4\cos 4\theta)$	Tetrafoil 0°
15	$\sqrt{10}(\rho^4\sin 4\theta)$	Tetrafoil 22.5°

Conventional optical correction with intraocular lenses will only comply with the fourth term of an optical system comprising the eye with an implanted lens. Glasses, contact lenses and some special intra ocular lenses provided with correction for astigmatism can further comply with terms five and six and substantially reducing Zernike polynomials referring to astigmatism.

The inventive method further includes to calculate the wavefront aberrations resulting from an optical system comprising said modeled bifocal intraocular lens and cornea and expressing it in a linear combination of polynomials and to determine if the bifocal intraocular lens has provided sufficient reduction in wavefront aberrations for one or more of the foci. If the reduction in wavefront aberrations is found to be insufficient, the lens will be re-modeled until one or several of the polynomial terms are sufficiently reduced. Remodeling the lens means that at least one lens design parameter affecting one or more of the foci is changed. These include the anterior surface shape and central radius, the posterior surface shape and central radius, the thickness of the lens, its refractive index, and the diameters and the step height of the diffractive zones. Typically, such remodeling includes changing the shape of a lens surface so it deviates from being spherical. There are several tools available in lens design that are useful to employ with the design method, such as the optical design software packages OSLO and Code-V. The formats of the Zernike polynomials associated with this application are listed in Table 1.

According to one embodiment, the inventive method comprises expressing at least one corneal surface as a linear combination of Zernike polynomials and thereby determining the resulting corneal wavefront Zernike coefficients, i.e. the coefficient of each of the individual Zernike polynomials that is selected for consideration. The bifocal lens is then modeled so that an optical system comprising of said model bifocal lens and cornea provides a wavefront having a sufficient reduction of selected Zernike coefficients for at least one of the foci. The method can optionally be refined with the further steps of calculating the Zernike coefficients of the Zernike polynomials representing a wavefront resulting from an optical system comprising the modeled intraocular bifocal lens and cornea and determining if the lens has provided a sufficient reduction of the wavefront Zernike coefficients for at least one foci of the optical system of cornea and lens; and optionally re-modeling said bifocal lens until a sufficient reduction in said coefficients is obtained for the at least one foci. Preferably, in this aspect the method considers Zernike polynomials up to the 4th order and aims to sufficiently reduce Zernike coefficients referring to spherical aberration and/or astigmatism terms. It is particularly preferable to sufficiently reduce the 11th Zernike coefficient of a wavefront from an optical system comprising cornea and said modeled multifocal intraocular lens, so as to obtain an eye sufficiently free from spherical aberration for at least one of the foci.

Alternatively, the design method can also include reducing higher order aberrations and thereby aiming to reduce Zernike coefficients of higher order aberration terms than the 4th order.

To achieve the desired reduction of aberrations, the bifocal intraocular lens is optimized with respect to unabberrated optical behavior of the optical system of the eye. In this respect, the optical behavior may be optimized for either one of the foci or both simultaneously. If the lens is optimized for the base focus, then the lens will give best optical result for far vision. Consequently when the lens is optimized for the near focus, the best performance is achieved in the near vision. Best over all performance is achieved when the lens is simultaneously optimized for both foci. The diffractive pattern of the bifocal lens may be formed independently of the lens surface that is modeled to reduce aberrations of the optical system, but it could also be formed on the same lens surface.

When designing lenses based on corneal characterizations from a selected population, preferably the corneal surfaces of each individual are expressed in Zernike polynomials describing the surface topography and there from the Zernike coefficients of the wavefront aberration are determined. From these results average Zernike wavefront aberration coefficients are calculated and employed in the design method, aiming at a sufficient reduction of selected such coefficients. In an alternative method according to the invention, average values of the Zernike polynomials describing the surface topography are instead calculated and employed in the design method. It is to be understood that the resulting lenses arriving from a design method based on average values from a large population have the purpose of substantially improving visual quality for all users. A lens having a total elimination of a wavefront aberration term based on an average value may consequently be less desirable and leave certain individuals with an inferior vision than with a conventional lens. For this reason, it can be suitable to reduce the selected Zernike coefficients only to certain degree or to a predetermined fraction of the average value.
According to another approach of the inventive design method, corneal characteristics of a selected population and the resulting linear combination of polynomials, e.g. Zernike polynomials, expressing each individual corneal aberrations can be compared in terms of coefficient values. From this result, a suitable value of the coefficients is selected and

employed in the inventive design method for a suitable lens. In a selected population having aberrations of the same sign such a coefficient value can typically be the lowest value within the selected population and the lens designed from this value would thereby provide improved visual quality for all individuals in the group compared to a conventional lens.

One embodiment of the method comprises selecting a representative group of patients and collecting corneal topographic data for each subject in the group. The method comprises further transferring said data to terms representing the corneal surface shape of each subject for a preset aperture size representing the pupil diameter. Thereafter a mean value of at least one corneal surface shape term of said group is calculated, so as to obtain at least one mean corneal surface shape term. Alternatively or complementary a mean value of at least one to the cornea corresponding corneal wavefront aberration term can be calculated. The corneal wavefront aberration terms are obtained by transforming corresponding corneal surface shape terms using a raytrace procedure. From said at least one mean corneal surface shape term or from said at least one mean corneal wavefront aberration term an bifocal intraocular lens capable of reducing, for at least one of its foci, said at least one mean wavefront aberration term of the optical system comprising cornea and lens is designed.

In one preferred embodiment of the present invention the method further comprises designing an average corneal model for the group of people from the calculated at least one mean corneal surface shape term or from the at least one mean corneal wavefront aberration term. It also comprises checking that the designed ophthalmic lens compensates correctly for the at least one mean aberration term. This is done by measuring these specific aberration terms of a wavefront having traveled through the model average cornea and the lens. The lens is redesigned if said at least one aberration term has not been sufficiently reduced in the measured wavefront for at least one of the foci.

Preferably one or more surface descriptive (asphericity describing) constants are calculated for the bifocal lens to be designed from the mean corneal surface shape term or from the mean corneal wavefront aberration terms for a predetermined radius. The spherical radius is determined by the refractive power of the lens.

The corneal surfaces are preferably characterized as mathematical models and the resulting aberrations of the corneal surfaces are calculated by employing the mathematical models and raytracing techniques. An expression of the corneal wavefront aberrations is thereby obtained, i.e. the wavefront aberrations of a wavefront having passed such a corneal surface. Dependent on the selected mathematical model different routes to calculate the corneal wavefront aberrations can be taken. Preferably, the corneal surfaces are characterized as mathematical models in terms of a conoid of rotation or in terms of polynomials or a combination thereof. More preferably, the corneal surfaces are characterized in terms of linear combinations of polynomials.

In one embodiment of the invention, the at least one nonspheric surface of the bifocal lens is designed such that the lens for at least one focus, in the context of the eye, provides to a passing wavefront at least one wavefront aberration term having substantially the same value but with opposite sign to a mean value of the same aberration term obtained from corneal measurements of a selected group of people, to which said patient is categorized. Hereby a wavefront arriving from the cornea of the patient's eye obtains a reduction in said at least one aberration term provided by the cornea after passing said bifocal lens. The used expression 'in the context of the eye' can mean both in the real eye and in a model of an eye.

In a specific embodiment of the invention, the wavefront obtains reduced aberration terms expressed in rotationally symmetric Zernike terms up to the fourth order. For this purpose, the surface of the bifocal intraocular lens is designed to reduce a positive spherical aberration term of a passing wavefront for at least one of the foci. In this text positive spherical aberration is defined such that a spherical surface with positive power produces positive spherical aberration. Preferably the bifocal lens is adapted to compensate for spherical aberration for at least one of the foci, and more preferably it is adapted to compensate for at least one term of a Zernike polynomial representing the aberration of a wavefront, preferably at least the 11^{th} Zernike term, see Table 1.

The selected groups of people could for example be a group of people belonging to a specific age interval, a group of people who will undergo a cataract surgical operation or a group of people who have undergone corneal surgery including but not limited to LASIK (laser in situ

keratomileunsis), RK (radialo keratoectomy) or PRK (photorefractive keratoectomy). The group could also be a group of people who have a specific ocular disease or people who have a specific ocular optical defect.

The lens is also suitably provided with optical powers. This is done according to conventional methods for the specific need of optical correction of the eye. Preferably the refractive power for the base focus of the lens is less than or equal to 34 diopters and the additional focus between 2 and 6 diopters. An optical system considered when modeling the lens to compensate for aberrations typically includes the average cornea and said lens, but in the specific case it can also include other optical elements including the lenses of spectacles, or an artificial correction lens, such as a contact lens, a corneal inlay or an implantable correction lens depending on the individual situation.

In an especially preferred embodiment the bifocal intraocular lens is designed for people who will undergo a cataract surgery. In this case it is has been shown that the average cornea from such a population is represented by a prolate surface following the formula:

$$z = \frac{(1/R)r^2}{1+\sqrt{1-(\frac{1}{R})^2(\mathbf{cc}+1)r^2}} + \mathbf{ad}r^4 + \mathbf{ae}r^6$$

wherein,

the conical constant cc has a value ranging between −1 and 0

R is the central lens radius and

ad and ae are polynomial coefficients additional to the conical constant.

In these studies the conic constant of the prolate surface ranges between about −0.05 for an aperture size (pupillary diameter) of 4 mm to about −0.18 for an aperture size of 7 mm. According to these results the bifocal intraocular lens to be designed should have a prolate surface following the same formula. Accordingly a bifocal intraocular lens suitable to improve visual quality by reducing at least spherical aberration for at least one focus for a cataract patient based on an average corneal value will have a prolate surface following the formula above. Since the cornea generally produces a positive spherical aberration to a wavefront in the eye, a bifocal intraocular lens for implantation into the eye will have

negative spherical aberration terms while following the mentioned prolate curve. As will be discussed in more detail in the exemplifying part of the specification, it has been found that an intraocular lens that can correct for 100% of a mean spherical aberration has a conical constant (cc) with a value of less than 0 (representing a modified conoid surface). For example, a 6 mm diameter aperture will provide a 20 diopter lens with conical constant value of about – 1.02.

In this embodiment, the bifocal intraocular lens is designed to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000698 mm to 0.000871 mm for a 3mm aperture radius, 0.0000161 mm to 0.00020 mm for a 2 mm aperture radius, 0.0000465 mm to 0.000419 mm for a 2,5 mm aperture radius and 0.0000868 mm to 0.00163 mm for a 3,5 mm aperture radius using polynomials expressed in table 1. These values were calculated for a model cornea having two surfaces with a refractive index of the cornea of 1.3375. It is possible to use optically equivalent model formats of the cornea without departing from the scope of the invention. For example one or more multiple surface corneas or corneas with different refractive indices could be used. The lower values in the intervals are here equal to the measured average value for that specific aperture radius minus one standard deviation. The higher values are equal to the measured average value for each specific aperture radius plus three standard deviations. The reason for selecting only minus one SD (= Standard Deviation) while selecting plus three SD is that in this embodiment it is convenient to only compensate for positive corneal spherical aberration and more than minus one SD added to the average value would give a negative corneal spherical aberration.

According to one embodiment of the invention the method further comprises the steps of measuring the at least one wavefront aberration term of one specific patient's cornea and determining if the selected group corresponding to this patient is representative for this specific patient. If this is the case the selected lens is implanted and if this is not the case a lens from another group is implanted or an individual lens for this patient is designed using this patient's corneal description as a design cornea. These method steps are preferred since then patients with extreme aberration values of their cornea can be given special treatments.

According to another embodiment, the present invention is directed to the selection of a bifocal intraocular lens of refractive powers, suitable for the desired optical correction that the patient needs, from a plurality of lenses having the same powers but different aberrations. The selection method is similarly conducted to what has been described with the design method and involves the characterizing of at least one corneal surface with a mathematical model by means of which the aberrations of the corneal surface is calculated. The optical system of the selected lens and the corneal model is then evaluated so as to consider if sufficient a reduction in aberrations is accomplished for at least one foci by calculating the aberrations of a wavefront arriving from such a system. If an insufficient correction is found a new lens is selected, having the same powers, but different aberrations. The mathematical models employed herein are similar to those described above and the same characterization methods of the corneal surfaces can be employed.

Preferably, the aberrations determined in the selection are expressed as linear combinations of Zernike polynomials and the Zernike coefficients of the resulting optical system comprising the model cornea and the selected lens are calculated. From the coefficient values of the system, it can be determined if the bifocal intraocular lens has sufficiently balanced the corneal aberration terms for at least one foci, as described by the Zernike coefficients of the optical system. If no sufficient reduction of the desired individual coefficients is found, these steps can be iteratively repeated by selecting a new lens of the same powers but with different aberrations, until a lens capable of sufficiently reducing the aberrations of the optical system for at least one foci is found. Preferably at least 15 Zernike polynomials up to the 4^{th} order are determined. If it is regarded as sufficient to correct for spherical aberration, only the spherical aberration terms of the Zernike polynomials for the optical system of cornea and bifocal intraocular lens are corrected. It is to be understood that the bifocal intraocular lens shall be selected so a selection of these terms become sufficiently small for the optical system comprising lens and cornea for at least one of the foci. In accordance with the present invention, the 11^{th} Zernike coefficient, a_{11}, can be substantially eliminated or brought sufficiently close to zero for at least one of the foci. This is a prerequisite to obtain a bifocal intraocular lens that sufficiently reduces the spherical aberration of the eye for at least one of the foci. The inventive method can be employed to correct for other types of aberrations than spherical aberration by considering other Zernike coefficients in an identical manner, for

example those signifying astigmatism, coma and higher order aberrations. Also higher order aberrations can be corrected dependent on the number of Zernike polynomials elected to be a part of the modeling, in which case a lens can be selected capable of correcting for higher order aberrations than the 4^{th} order.

According to one important aspect, the selection method involves selecting lenses from a kit of lenses having lenses with a range of powers and a plurality of lenses within each power combinations for far and near foci having different aberrations. In one example the lenses within each power combination have anterior surfaces with different aspherical components. If a first lens does not exhibit sufficient reduction in aberration for at least one of the foci, as expressed in suitable Zernike coefficients, then a new lens of the same power combination, but with a different surface (aspheric component) is selected. The selection method can if necessary be iteratively repeated until the best lens is found or the studied aberration terms are reduced below a significant borderline value for at least one of the foci. In practice, the Zernike terms obtained from the corneal examination will be directly obtained by the ophthalmic surgeon and by means of an algorithm they will be compared to known Zernike terms of the lenses in the kit. From this comparison the most suitable lens in the kit can be found and implanted. Alternatively, the method can be conducted before cataract surgery and data from the corneal estimation is sent to a lens manufacturer for production of an individually tailored lens.

The present invention further pertains to a bifocal intraocular lens having at least one nonspherical surface capable of transferring, for at least one foci, a wavefront having passed through the cornea of the eye into a substantially spherical wavefront with its center at the retina of the eye. Preferably, the wavefront is substantially spherical with respect to aberration terms expressed in rotationally symmetric Zernike terms up to the fourth order.

In accordance with an especially preferred embodiment, the invention relates to a bifocal intraocular lens, which has at least one surface, when expressed as a linear combination of Zernike polynomial terms using the normalized format, that has a negative 11th term of the fourth order with a Zernike coefficient a_{11} that that can balance a positive corresponding term

of the cornea, to obtain sufficient reduction of the spherical aberration for at least one foci of the eye after implantation. In one aspect of this embodiment, the Zernike coefficient a_{11} of the bifocal lens is determined so as to compensate for an average value resulting from a sufficient number of estimations of the Zernike coefficient a_{11} in several corneas. In another aspect, the Zernike coefficient a_{11} is determined to compensate for the individual corneal coefficient of one patient. The bifocal lens can accordingly be tailored for an individual with high precision.

The invention further relates to another method of providing a patient with a bifocal intraocular lens, which at least partly compensates for the aberrations of the eye for at least one of the foci. This method comprises removing the natural lens from the eye. Surgically removing of the impaired lens can be performed by using a conventional phacoemulsification method. The method further comprises measuring the aberrations of the aphakic eye, not comprising the a lens, by using a wavefront sensor. Suitable methods for wavefront measurements are found in J.Opt.Soc.Am., 1994, Vol. 11(7), pp. 1949-57 by Liang et. al. Furthermore, the method comprises selecting from a kit of lenses a lens that at least partly compensates for the measured aberrations for at least one of the foci and implanting said lens into the eye. The kit of lenses comprises lenses of different powers and different aberrations and finding the most suitable lens can be performed in a manner as earlier discussed. .Alternatively, an individually designed lens for the patient can be designed based on the wavefront analysis of the aphakic eye for subsequent implantation. This method is advantageous, since no topographical measurements of the cornea are need to be done and the whole cornea, including the front and back surfaces, is automatically considered.

The lenses according to the present invention can be manufactured with conventional methods. In one embodiment they are made from soft, resilient material, such as silicones or hydrogels. Examples of such materials suitable for foldable intraocular lenses are found in US patent No. 5,444,106 or in US Patent No. 5,236,970. Manufacturing of nonspherical silicone lenses or other foldable lenses can be performed according to US Patent No. 6,007,747. Alternatively, the lenses according to the present invention can be made of a more rigid material, such as poly(methyl)methacrylate. The skilled person can readily identify alternative

materials and manufacturing methods, which will be suitable to employ to produce the inventive aberration reducing lenses.

As is shown in the following examples, the bifocal intraocular lens according to the present invention (BRAIOL) outperforms conventional BIOLs with respect to Modulation Transfer Function characteristics. More specifically it has been found that the BRAIOL has a modulation of at least 0.2 for both foci at a spatial frequency of 50 cycles per millimetre, when designed such that the light distribution between the two foci is 50:50%. The measurements are performed in an average eyemodel using a 5mm aperture. Surprisingly it has further been found that the sum of the modulation at 50c/mm for the two or more foci is more than 0.40, and in some cases even above 0.50, independent of the light distribution, when measured in the model specified above. The fact that the sum of the modulation at 50c/mm is independent of light distribution is illustrated for the case where the light distribution has a limiting value of 100:0%, which is equivalent to a monofocal lens. Conventional lenses and lenses correcting spherical aberration were designed, manufactured and measured. In this situation, the conventional lens has a modulation at 50c/mm of 0.21, while the design optimized for spherical aberration shows a modulation of 0.6, equivalent to the sum of the designed bifocal lens.

Furthermore, the evaluation experiments have revealed that the wavefronts of the 2 foci of a bifocal lens are independent with respect to some of the Zernike terms, but that some of the Zernike terms are coupled or equal for both. The far majority of this difference is in the 'defocus' term, which represents the 4 diopters difference between the focal points. In the design process it has been found that the spherical aberration part of the wavefront is not very different for the 2 wavefronts. This is also true for all other aberrations, apart from defocus, tilt and the piston term. Consequently the present invention makes it possible to provide a lens with reduced aberrations in essentially the same scale for all foci.

Examples:

General:

A bifocal intraocular lens which corrects the corneal spherical aberration (BRAIOL) can be modeled based on a conventional bifocal lens (BIOL), in this case the bifocal model 811E, Pharmacia Corp., which is a diffractive lens design made of Poly(MethylMethAcrylate) material. The power add of this lens is +4 diopter for reading, which corresponds to reading spectacles of 3 diopters. In this example, the design is adapted to be used for a silicone material. As a consequence, the step heights of the diffractive surface profile are increased with the ratio of the reduced refractive indices of the 2 materials.

The lens optic is a combination of a biconvex lens and a diffractive lens. The diffractive surface profile is superimposed onto the spherical posterior surface of the optic. The diffractive surface profile can be described using conventional sag equations. Examples of equations for the surface profile are described in the literature. For instance, Cohen (1993, 'Diffractive bifocal lens design', Optom Vis Sci 70(6): 461:8) describes the diffractive profile with the equation:

$$S_d(r) = h^* \{N - r^2/w^2\}$$

wherein
r is the distance from the optical axis
h is the maximum profile height (stepheight)
N is the zone number
w is the width of the first zone

Other equations are also possible. The type of diffractive profile is not relevant for the working principles. The diffractive profile is superimposed onto a normal spherical surface, so that the total sag equation becomes

$$S(r) = S_s(r) + S_d(r),$$

where $S_s(r)$ is the sag equation of a spherical biconvex lens:

$$S_s(r) = \frac{cv * r^2}{1 + \sqrt{1 - cv^2 * r^2}}$$

cv=1/R is the curvature of the lens optic

R is the radius of curvature of the lens optic

The radius of curvature of the diffractive bifocal lens is equal to the radius of curvature of a monofocal lens having the same power.

Throughout the example the light distribution between the two foci was chosen to be 50%:50%, and the target power add for near vision was +4D. Other light distributions can be chosen, without changing the principles of how the methods work. In practice, light distribution between 70%:30% to 30%:70% and near vision add between 3 and 4 diopters have been on the market. But also outside these ranges the methods should be applicable.

Throughout the example, data from characterization of corneas conducted on a selected population, was used to calculate the resulting corneal aberrations. The anterior corneal surface shapes of a population of 71 cataract patients were measured using corneal topography. The surface shapes were described using Zernike polynomials. Each surface shape was converted into a wavefront aberration. Also the wavefront aberration was described in Zernike polynomials.

The method is described in example 4 of the patent application WO 01/89424 A1.

The terms of the Zernike polynomials are expressed in wavelengths (λ), using the reference wavelength of 550 nanometers (λ=550nm).

The target in this example is to correct the corneal spherical aberration by the bifocal IOL. In order to evaluate the designs, a theoretical design cornea was developed, similar to the one described in example 4 of the patent application WO 01/89424 A1. In the case of modelling a monofocal IOL the design cornea can be a 1-surface model, wherein the refractive index of the cornea is the keratometry index of 1.3375. For diffractive lenses it is essential to use the real in vivo refractive index surrounding the posterior (diffractive) lens surface. Therefore, a 2-surface model was developed, which has the same on-axis aberrations as the 1-surface model.

The theoretical performance of the prototype design in terms of symmetric Zernike coefficients was evaluated for an IOL having a base power (far vision) of 20 Diopters. An IOL having this power is close to what is suitable for most cataract patients. However, the design method and resulting IOL is similar for other lens powers. Typically, IOL powers range from 4 to 34 diopters, sometimes extend to −10 to +40 diopters and can be occasionally produced even outside these ranges.

Example 1:

In one embodiment, the lens is biconvex, having radii of curvature of 12.15 mm on both the anterior and posterior surface and a central thickness of 1.1 mm. The anterior surface is asphcrized. In an iterative process, the aberration of the optical system of design cornea and bifocal IOL are optimised in order to reduce the wavefront aberration in the far focus position, in this example the Zernike term Z_{11}, representing the spherical aberration. In this process, the asphericity of the anterior lens surface is used as the design parameter. The asphericity of the anterior surface is described by a conic constant. The sag equation of the anterior surface is:

$$S(r) = \frac{cv * r^2}{1 + \sqrt{1 - cv^2 (cc+1) r^2}}$$

wherein cc is the conic constant

Using commercially available optical design software, the variable cc can be optimized to minimize the Zernike term Z_{11} for the far vision focal point. The variable cc was determined for an aperture size of 5.1 mm. The anterior surface of this BRAIOL has been modified in such a way that the spherical aberration of the system (cornea+lens) is now approximately equal to 0. The resulting value of the conic constant was −29.32. The Z_{11} coefficient representing spherical aberration for the conventional IOL in the eye model is 3.8 λ, while the same coefficient for the eye model with the designed BRAIOL is 0.01 λ, representing a reduction of the spherical aberration by a factor of 380. The same process as described above for can similarly be performed for any other lens power.

Example 2:

In another embodiment, the lens is biconvex, having radii of curvature of 12.15 mm on both the anterior and posterior surface and a central thickness of 1.1 mm. The diffractive posterior surface is asphericized. In an iterative process, the aberration of the optical system of design cornea and bifocal IOL are optimised in order to reduce the wavefront aberration, in this example the Zernike term Z_{11}, representing the spherical aberration, as well as the symmetrical higher order terms Z_{22} and Z_{37}. In this process, the asphericity of the posterior lens surface is used as the design parameter. The asphericity of the posterior surface is described by a conic constant and 2 higher order terms. The total sag equation is:

$$S(r)=\frac{cv*r^2}{1+\sqrt{1-cv^2(cc+1)r^2}}+ad*r^4+ae*r^6+S_d(r)$$

wherein:
cc is the conic constant
ad is the 4th order aspheric coefficient
ae is the 6th order aspheric coefficient

Using commercially available optical design software, the variables **cc**, **ad** and **ae** can be optimized to minimize the Zernike terms Z_{11}, Z_{22} and Z_{37} simultaneously in the far focal point. The variables are determined for an aperture size of 5.1 mm. The posterior surface of this BRAIOL has been modified in such a way that the spherical aberration and the 2 higher order terms of the system (cornea+lens) is now approximately equal to 0. The optimisation resulted in the posterior surface aspheric coefficients presented in table 2:

Table 2

Aspheric coefficient	Value
Cc	-2.53
Ad	9.4e-4
Ae	-5.1e-6

The optical results can be expressed as a reduction in the Zernike coefficients between the conventional BIOL (using cc=ad=ae=0) and the newly designed BRAIOL, and are presented in table 3:

Table 3

Zernike coefficient	Conventional BIOL	BRAIOL
Z_{11}	3.8 λ	0.01 λ
Z_{22}	0.11 λ	-0.003 λ
Z_{37}	-0.07 λ	-0.07 λ

Table 3 shows a large reduction of aberration represented by the coefficients Z_{11} and Z_{22} and no significant reduction of coefficient Z_{37}. The same process as described above for can similarly be performed for any other lens power.

Example 3: both

In another embodiment, the lens is biconvex, having an anterior radius of curvature of 12.15 mm, a posterior radius of curvature of 12.59 and a central thickness of 1.1 mm. The diffractive profile is located on the posterior surface and the anterior surface is asphcrized. In an iterative process, the aberration of the optical system of design cornea and bifocal IOL are optimised in order to reduce the wavefront aberration, in this example the Zernike term Z_{11}, representing the spherical aberration, as well as the symmetrical higher order terms Z_{22} and Z_{37}. In this process, the asphericity of the anterior lens surface is used as the design parameter. The asphericity of the anterior surface is described by a conic constant and 2 higher order terms. The sag equation of the anterior surface is:

$$S(r) = \frac{cv * r^2}{1+\sqrt{1-cv^2(cc+1)r^2}} + ad * r^4 + ae * r^6$$

wherein:

cc is the conic constant

ad is the 4th order aspheric coefficient

ae is the 6th order aspheric coefficient

Using commercially available optical design software, the variables **cc**, **ad** and **ae** can be optimized to minimize the Zernike term Z_{11}, Z_{22} and Z_{37} simultaneously. Furthermore, in this embodiment the Zernike terms for both far and near focal points were taken into account in the optimisation. In this way both far and near focal point were optimised simultaneously. As an extra criterion, weight factors were added, to secure that the lowest order terms were reduced most drastically. The weight factors were 1, 0.1 and 0.01 for Z_{11}, Z_{24} and Z_{37} respectively. The variables are determined for an aperture size of 5.1 mm. The posterior surface of this BRAIOL has been modified in such a way that the spherical aberration and the 2 higher order terms of the system (cornea+lens) is now approximately equal to 0. The optimisation resulted in the posterior surface aspheric coefficients, presented in table 4:

Table 4

Aspheric coefficient	Value
cc	-1.02
ad	-4.9e-4
ae	-4.9e-5

The optical results can be expressed as a reduction in the Zernike coefficients between the conventional BIOL (using cc=ad=ae=0) and the newly designed BRAIOL. Since both far and near are taken into account, the vector sum of the far and near Zernike coefficients are displayed in table 5:

Table 5

Zernike coefficient	Conventional BIOL	BRAIOL
Z_{11}	5.3 λ	0.08 λ
Z_{22}	0.15 λ	0.43 λ
Z_{37}	0.08 λ	0.08 λ

Table 5 shows a large reduction of aberration represented by the coefficients Z_{11} and no significant reduction of coefficient Z_{22} and Z_{37}, indicating that Zernike term Z_{11} was minimized on the cost of term Z_{22}, while Z_{37} was as low as reasonably possible already.

The optical quality was further characterized by calculating the modulation transfer function in the eye model, using an aperture of 5 mm (fig 1)

These calculation results show that, when compared with a conventional BIOL, the modulation transfer function of the BRAIOL is increased with at least by a factor 2. Prototype lenses of this design were made and the modulation transfer function was also measured in an eye model. The physical eye model was constructed to have the same wavefront aberrations as the design model based on the population of 71 cataract patients. The focal points were determined by focussing at a spatial frequency of 25, 50, 100 cycles per millimetre. Fig. 2 shows the results. The results are the averages of 8 BRIOL lenses and 10 conventional BIOL lenses, with 3 measurement per lens. The figure 2 confirms the gain in optical quality that can be achieved with the BRAIOL.

This example clearly shows that the RAIOL design principles can be successfully applied on bifocal (or multifocal) lenses. Three approaches were used: one design with the anterior lens shape optimized for Zernike coefficient Z_{11} for far focus combined with a diffractive posterior surface. Alternatively a new posterior lens shape was generated by optimizing the wavefront aberrations of Zernike coefficients Z_{11}, Z_{22} and Z_{37}. Finally, a new anterior lens shape was generated by optimizing for the Zernike coefficients Z_{11}, Z_{22} and Z_{37} and for the far as well as the near focus. The performance of these 3 types of lenses, in terms of MTF, showed to be essentially comparable. It was also demonstrated that the improvement optical performance as calculated in theory can be confirmed by measurement of prototype lenses.

The improvement of the BRAIOL, compared to BIOL (model 811E), is significant. However the improvement is greater for the larger pupils (larger than 3mm).

The optical form chosen for the new BRAIOL design is an equiconvex lens made from a silicone with refractive index of 1.458. The spherical aberration of an average cornea is balanced by the BRAIOL lens yielding a system without spherical aberration. The front surface of the lens is modified such that the optical path lengths of all on-axis rays within the design aperture are the same producing a point focus. This feature can be achieved with many

lens forms. The BRAIOL lens could therefore be designed on a convex-plano, plano-convex, non-equiconvex lens or any other design yielding a positive lens. The BRAIOL concept could also be extended in order to encompass a negative lens used to correct the refractive errors of the eye. The front surface or back surface could also be modified to produce the needed change in optical path difference that neutralizes the spherical aberration. There are therefore many possible designs that would achieve the goals of the BRAIOL lens design.

A number of embodiments have been described above. However, it is obvious that the design could be varied without deviating from the inventive idea of providing a multifocal ophthalmic lens correcting aberration in the eye system.

Therefore the present invention should not be regarded as restricted to the above disclosed embodiments, but can be varied within the scope of the appended claims. For example, the BIOL can be designed to compensate for non-symmetrical Zernike terms. This would required making surfaces being rotationally non-symmetric, which is within the state of the art production techniques, demonstrated by cylindrical lenses being currently on the market.

Claims

1. A method of designing a multifocal ophthalmic lens with one base focus and at least one additional focus, capable of reducing aberrations of the eye for at least one of the foci after its implantation, comprising the steps of-

   (i) characterizing at least one corneal surface as a mathematical model;

   (ii) calculating the resulting aberrations of said corneal surface(s) by employing said mathematical model;

   (iii) modelling the multifocal ophthalmic lens such that a wavefront arriving from an optical system comprising said lens and said at least one corneal surface obtains reduced aberrations for at least one of the foci.

2. A method according to claim 1, wherein the ophthalmic lens is a multifocal intraocular lens.

3. A method according to claim 1 or 2, comprising determining the resulting aberrations of said corneal surface(s) in terms of a wavefront having passed said cornea.

4. A method according to any of the claims 1 to 3, wherein said corneal surface(s) is(are) characterized in terms of a conoid of rotation.

5. A method according to any of the claims 1 to 3 wherein said corneal surface(s) is(are) characterized in terms of polynomials.

6. A method according to claim 5, wherein said corneal surface(s) is(are) characterized in terms of a linear combination of polynomials.

7. A method according to any of the preceding claims, wherein said optical system further comprises complementary means for optical correction, such as spectacles or

an ophthalmic correction lens.

8. A method according to any of the preceding claims, wherein estimations of corneal refractive power and axial eye length designate the selection of the optical powers for the multifocal intraocular lens.

9. A method according to any of the preceding claims, wherein the multifocal intraocular lens is modelled by selecting a suitable aspheric component for the anterior surface.

10. A method according to any of the preceding claims, including characterizing the front corneal surface of an individual by means of topographical measurements and expressing the corneal aberrations as a combination of polynomials.

11. A method according to any of the preceding claims, including characterizing front and rear corneal surfaces of an individual by means of topographical measurements and expressing the total corneal aberrations as a combination of polynomials.

12. A method according to any of the preceding claims, including characterizing corneal surfaces of a selected population and expressing average corneal aberrations of said population as a combination of polynomials.

13. A method according to any of the preceding claims, comprising the further steps of :

(vii) calculating the aberrations resulting from an optical system comprising said modelled intraocular lens and cornea;
(iix) determining if the modelled intraocular lens has provided sufficient reduction in aberrations; and optionally re-modeling the intraocular lens until a sufficient reduction is obtained.

14. A method according to claim 13, wherein said aberrations are expressed as a linear combination of polynomials.

15. A method according to claim 13 or 14, wherein the re-modeling includes modifying one or several of the anterior surface shape and central radius, the posterior surface shape and central radius, lens thickness and refractive index of the lens.

16. A method according to any of the claims 14 to 15, wherein the re-modelling includes modifying the anterior surface of the lens.

17. A method according to any of the claims 14 to 16, wherein said polynomials are Seidel or Zernike polynomials.

18. A method according to claim 17, comprising modelling a lens such that an optical system comprising said model of intraocular lens and cornea provides reduction of spherical terms as expressed in Seidel or Zernike polynomials in a wave front having passed through the system.

19. A method according to claim 17 or 18, comprising the steps of:

expressing the corneal aberrations as a linear combination of Zernike polynomials;

determining the corneal wavefront Zernike coefficients;

modelling the multifocal intraocular lens such that an optical system comprising said model lens and cornea provides a wavefront having a sufficient reduction of Zernike coefficients in at least 1 of the foci.

20. A method according to claim 19, further comprising the steps of :

calculating the Zernike coefficients of a wavefront resulting from an optical system comprising the modelled multifocal intraocular lens and cornea;

determining if said intraocular lens has provided a sufficient reduction of Zernike coefficients; and optionally re-modelling said lens until a sufficient reduction is said

coefficients are obtained.

21. A method according to claim 20, comprising sufficiently reducing Zernike coefficients referring to spherical aberration.

22. A method according to any of the claims 19 to 21 comprising sufficiently reducing Zernike coefficients referring to aberrations above the fourth order.

23. A method according to any of the claims 19 to 22 comprising sufficiently reducing the 11th Zernike coefficient of a wavefront front from an optical system comprising cornea and said modelled intraocular lens, so as to obtain an eye sufficiently free from spherical aberration.

24. A method according to any of the preceding claims, wherein the reduction of aberrations is optimized for one of the foci.

25. A method according to claim 24, wherein the reduction of aberrations is optimized for the base focus.

26. A method according to claim 24, wherein the reduction of aberrations is optimized for one of the at least one additional focus.

27. A method according to any of the claims 1 to 23, wherein the reduction of aberrations is optimized for the base focus and the at least one additional focus, simultaneously.

28. A method according to any of the preceding claims, wherein the modelling of the multifocal intraocular lens comprises modelling the lens as a multifocal lens of diffractive type.

29. A method according to claim 28, wherein the diffractive pattern is formed on the anterior and/or posterior surface of the lens.

30. A method according to claim 29, wherein the diffractive pattern is formed on the lens surface that is modelled to reduce aberrations of the optical system.

31. A method according to claim 29, wherein the diffractive pattern is formed on one surface of the lens and the other surface of the lens is modelled to reduce aberrations of the optical system.

32. A method according to any of the claims 1 to 28, wherein the modelling of the multifocal intraocular lens comprises modelling the lens as a multifocal lens of refractive type with anular rings with different radii of curvatures.

33. A method according to claim 32 wherein the anular rings are formed on the lens surface that is modelled to reduce aberrations of the optical system.

34. A method according to claim 32 wherein the anular rings are formed on one surface of the lens and the other surface is modelled to reduce aberrations of the optical system.

35. A method according to any of the claims 1 to 34, wherein the modelling of the multifocal intraocular lens comprises modelling a bifocal lens.

36. A method according to any of the claims 1 to 35, wherein the modeling of the multifocal intraocular lens provides a lens with substantially the same reduced aberrations for all foci.

37. A method according to any of the claims 1 to 36, wherein the sum of the modulation for the two or more foci is more than 0.40, at a spatial frequency of 50 cycles per millimetre, when the measurements are performed in an average/individual eye model using a 5mm aperture.

38. A method according to claim 37, wherein the sum of the modulation for the two or more foci is more than 0.50.

39. A method according to claim 37 or 38, wherein the modelling of the multifocal intraocular lens comprises modelling a bifocal lens with a light distribution of 50-50% between the two foci, and the modulation is at least 0.2 for each focus.

40. A method of selecting a multifocal intraocular lens that is capable of reducing aberrations of the eye for at least one of the foci after its implantation comprising the steps of:

(i) characterizing at least one corneal surface as a mathematical model;

(ii) calculating the resulting aberrations of said corneal surfaces(s) by employing said mathematical model;

(iii) selecting an intraocular lens having a suitable configuration of optical powers from a plurality of lenses having the same power configurations, but different aberrations;

(iv) determining if an optical system comprising said selected lens and corneal model sufficiently reduces the aberrations.

41. A method according to claim 40, comprising determining the resulting aberrations of said corneal surface(s) in a wavefront having passed said cornea.

42. A method according to claim 40 or 41 further comprising the steps of:

(v) calculating the aberrations of a wave front arriving from an optical system of said selected lens and corneal model;

(vi) determining if said selected multifocal intraocular lens has provided a sufficient reduction in aberrations in a wavefront arriving from said optical system for at least one of the foci; and optionally repeating steps (iii) and (iv) by selecting at least one new lens having the same optical power until finding a lens capable of sufficiently

reducing the aberrations.

43. A method according to any of the claims 40 to 42, wherein said corneal surface(s) is(are) characterized in terms of a conoid of rotation.

44. A method according to any of the claims 40 to 42 wherein said corneal surface(s) is(are) characterized in terms of polynomials.

45. A method according to any of the claims 40 to 42, wherein said corneal surface(s) is(are) characterized in terms of a linear combination of polynomials.

46. A method according to any of the claims 40 to 45, wherein said optical system further comprises complementary means for optical correction, such as spectacles or an ophthalmic correction lens.

47. A method according to any of the claims 40 to 46, wherein corneal refractive power and axial eye length estimations designate the selection of lens optical powers for the multifocal intraocular lens..

48. A method according to claim 39 or 45, wherein an optical system comprising said corneal model and selected multifocal intraocular lens provides for a wavefront substantially reduced from aberrations for at least one of the foci, as expressed by at least one of said polynomials.

49. A method according to any of the claims 40 to 48 including characterizing the front corneal surface of an individual by means of topographical measurements and expressing the corneal aberrations as a combination of polynomials.

50. A method according to any of the claims 40 to 49 including characterizing front and rear corneal surfaces of an individual by means of topographical measurements and expressing the total corneal aberrations as a combination of polynomials.

51. A method according to any of the claims 40 to 46, including characterizing corneal surfaces of a selected population and expressing average corneal aberrations of said population as a combination of polynomials.

52. A method according to claim 45 or 51, wherein said polynomials are Seidel or Zernike polynomials.

53. A method according to claim 52, comprising the steps of:

(i) expressing the corneal aberrations as a linear combination of Zernike polynomials;
(ii) determining the corneal Zernike coefficients;
(iii) selecting the multifocal intraocular lens such that an optical system comprising said lens and cornea provides a wavefront having a sufficient reduction in Zernike coefficients for at least one of the foci.

54. A method according to claim 53, further comprising the steps of:

(iv) calculating the Zernike coefficients resulting from an optical system comprising the modelled multifocal intraocular lens and cornea;
(v) determining if said intraocular lens has provided a reduction of Zernike coefficients; and optionally selecting a new lens until a sufficient reduction is said coefficients is obtained.

55. A method according to claim 53 or 54, comprising determining Zernike polynomials up to the 4^{th} order.

56. A method according to any of the claims 53 to 55 comprising sufficiently reducing Zernike coefficients referring to spherical aberration.

57. A method according to any of the claims 53 to 56 comprising sufficiently reducing Zernike coefficients above the fourth order.

58. A method according to any of the claims 53 to 57 comprising sufficiently reducing the 11th Zernike coefficient of a wavefront front from an optical system comprising model cornea and said selected intraocular lens, so as to obtain an eye sufficiently free from spherical aberration for at least one of the foci.

59. A method according to any of the claims 53 to 58 comprising selecting a intraocular lens such that an optical system comprising said intraocular lens and cornea provides reduction of spherical aberration terms as expressed in Seidel or Zernike polynomials in a wave front having passed through the system.

60. A method according to any of the claims 53 to 59, wherein reduction in higher aberration terms is accomplished.

61. A method according to any of the claims 40 to 60 characterized by selecting an multifocal intraocular lens from a kit comprising lenses with a suitable range of power configurations and within each range of power configurations a plurality of lenses having different aberrations.

62. A method according to claim 61, wherein said aberrations are spherical aberrations.

63. A method according to claim 62, wherein said lenses within each range of power configurations have surfaces with different aspheric components.

64. A method according to claim 63, wherein said surfaces are the anterior surfaces.

65. A method according to any of the claims 40 to 64, wherein the reduction of aberrations is optimized for one of the foci.

66. A method according to claim 65, wherein the reduction of aberrations is optimized for the base focus.

67. A method according to claim 65, wherein the reduction of aberrations is optimized for one of the at least one additional focus.

68. A method according to any of the claims 40 to 64, wherein the reduction of aberrations is optimized for the base focus and the at least one additional focus, simultaneously.

69. A method according to any of the claims 40 to 68, wherein the multifocal intraocular lens is a multifocal lens of diffractive type.

70. A method according to claim 69, wherein the diffractive pattern is formed on the anterior and/or posterior surface of the lens.

71. A method according to claim 70, wherein the diffractive pattern is formed on the lens surface that is modelled to reduce aberrations of the optical system.

72. A method according to claim 70, wherein the diffractive pattern is formed on one surface of the lens and the other surface of the lens is modelled to reduce aberrations of the optical system.

73. A method according to any of the claims 40 to 68, wherein the multifocal intraocular lens is a multifocal lens of refractive type with anular rings with different radii of curvatures.

74. A method according to claim 73 wherein the anular rings are formed on the lens surface that is modelled to reduce aberrations of the optical system.

75. A method according to claim 73 wherein the anular rings are formed on one surface of the lens and the other surface is modelled to reduce aberrations of the optical system.

76. A method according to any of the claims 40 to 75, wherein the multifocal intraocular lens is a bifocal lens.

77. A method according to any of the claims 40 to 35, wherein the multifocal intraocular lens has substantially the same reduced aberrations for all foci.

78. A method according to any of the claims 40 to 77, wherein the sum of the modulation for the two or more foci is more than 0.40, at a spatial frequency of 50 cycles per millimetre, when the measurements are performed in an average/individual eye model using a 5mm aperture.

79. A method according to claim 78, wherein the sum of the modulation for the two or more foci is more than 0.50.

80. A method according to claim 78 or 79, wherein the lens is bifocal with a light distribution of 50-50% between the two foci and the modulation is at least 0.2 for each focus.

81. A method of designing a multifocal ophthalmic lens suitable for implantation into the eye, characterized by the steps of:

selecting a representative group of patients;

collecting corneal topographic data for each subject in the group;

transferring said data to terms representing the corneal surface shape of each subject for a preset aperture size;

calculating a mean value of at least one corneal surface shape term of said group, so as to obtain at least one mean corneal surface shape term and/or calculating a mean value of at least one to the cornea corresponding corneal wavefront aberration term, each corneal wavefront aberration term being obtained by transforming corresponding

through corneal surface shape terms;

from said at least one mean corneal surface shape term or from said at least one mean corneal wavefront aberration term designing a multifocal ophthalmic lens capable of reducing said at least one mean wavefront aberration term of the optical system comprising cornea and lens for at least one of the foci.

82. Method according to claim 81, characterized in that it further comprises the steps of:

designing an average corneal model for the group of people from the calculated at least one mean corneal surface shape term or from the at least one mean corneal wavefront aberration term;

checking that the designed multifocal ophthalmic lens compensates correctly for the at least one mean aberration term for at least one of the foci by measuring these specific aberration terms of a wavefront having travelled through the model average cornea and the lens and redesigning the multifocal lens if said at least one aberration term not has been sufficiently reduced in the measured wavefront.

83. Method according to claim 81 or 82, characterized by calculating an aspheric surface descriptive constant for the lens to be designed from the mean corneal surface shape terms or from the mean corneal wavefront aberration terms for a predetermined radius.

84. Method according to any one of the claims 81-83, characterized by selecting people in a specific age interval to constitute the group of people.

85. Method according to any one of the claims 81-84, characterized by selecting people who will undergo a cataract surgery to constitute the group of people.

86. Method according to any one of the claims 81-85, characterized by designing the lens specifically for a patient that has undergone corneal surgery and therefore selecting

people who have undergone corneal surgery to constitute the group of people.

87. Method according to any one of the claims 81-86, characterized by selecting people who have a specific ocular disease to constitute the group of people.

88. Method according to any one of the claims 81-87, characterized by selecting people who have a specific ocular optical defect to constitute the group of people.

89. Method according to any one of the claims 81-88, characterized in that it further comprises the steps of:

measuring the at least one wavefront aberration term of one specific patient's cornea;

determining if the selected group corresponding to this patient is representative for this specific patient and if this is the case implant the multifocal lens designed from these average values and if this not is the case implant a multifocal lens designed from average values from another group or design an individual lens for this patient.

90. Method according to any one of the claims 81-89, characterized by providing the multifocal lens with at least one nonspheric surface that reduces at least one positive aberration term of an incoming nonspheric wavefront for at least one of the foci.

91. Method according to claim 90, characterized in that said positive aberration term is a positive spherical aberration term.

92. Method according to any one of the claims 81-91, characterized by providing the multifocal lens with at least one nonspheric surface that reduces at least one term of a Zernike polynomial representing the aberration of an incoming nonspheric wavefront for at least one of the foci.

93. Method according to claim 92, characterized by providing the lens with at least one nonspheric surface that reduces the 11th normalized Zernike term representing the

spherical aberration of an incoming nonspheric wavefront.

94. A method according to any of claims 81-93 characterized by designing a multifocal lens to reduce, for at least one of the foci, spherical aberration in a wavefront arriving from an average corneal surface having the formula:

$$z = \frac{(1/R)r^2}{1+\sqrt{1-(\frac{1}{R})^2(\mathbf{cc}+1)r^2}} + \mathbf{ad}r^4 + \mathbf{ae}r^6$$

wherein the conical constant cc has a value ranging between –1 and 0, R is the central corneal radius and ad and ae are aspheric constants.

95. A method according to claim 94, wherein the conical constant (cc) ranges from about –0.05 for an aperture size (pupillary diameter) of 4 mm to about –0.18 for an aperture size of 7 mm.

96. Method according to claim 81-95, characterized by providing the multifocal lens with a surface described by a conoid of rotation modified conoid having a conical constant (cc) less than 0.

97. Method according to any one of the claims 81-96, characterized by providing the multifocal lens with a, for the patient, suitable power configuration,.

98. Method according to any one of the claims 81-97, characterized by designing the multifocal lens to balance, for at least one of the foci, the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000698 mm to 0.000871 mm for a 3 mm aperture radius.

99. Method according to any one of the claims 81-97, characterized by designing the multifocal lens to balance, for at least one of the foci, the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000161 mm to 0.000200

mm for a 2 mm aperture radius.

100. Method according to any one of the claims 81-97, characterized by designing the multifocal lens to balance, for at least one of the foci, the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000465 mm to 0.000419 mm for a 2,5 mm aperture radius.

101. Method according to any one of the claims 81-97, characterized by designing the multifocal lens to balance, for at least one of the foci, the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000868 mm to 0.00163 mm for a 3,5 mm aperture radius.

102. A multifocal ophthalmic lens obtained in accordance with any of the preceding claims, capable of, for at least one of its foci, transferring a wavefront having passed through the cornea of the eye into a substantially spherical wavefront having its center in the retina of the eye.

103. A multifocal ophthalmic lens with one base focus and at least one additional focus, characterized in that

the shape of the lens is modelled such that the resulting aberrations are reduced for at least one of the foci in an optical system comprising said multifocal lens and a model cornea having aberration terms.

104. A multifocal intraocular lens according to claim 103.

105. A multifocal intraocular lens according to claim 104 wherein said corneal model includes average aberration terms calculated from characterizing individual corneas for a suitable population, and expressing them in mathematical terms so as to obtain

106. A multifocal intraocular lens according to claim 105, wherein said aberration terms is a linear combination of Zernike polynomials.

107. A multifocal intraocular lens according to claim 106 capable of reducing aberration terms expressed in Zernike polynomials of said corneal model, such that a wavefront arriving from an optical system comprising said model cornea and said lens obtains substantially reduced spherical aberration.

108. A multifocal intraocular lens according to claim 107 capable of reducing the 11th Zernike term of the 4th order.

109. A multifocal intraocular lens according to any of the claims 103 to 108, adapted to replace the natural lens in a patient's eye, said multifocal intraocular lens having at least one nonspheric surface, this at least one nonspheric surface being designed such that the lens for at least one of the foci, in the context of the eye, provides to a passing wavefront at least one wavefront aberration term having substantially the same value but with opposite sign to a mean value of the same aberration term obtained from corneal measurements of a selected group of people, to which said patient is categorized, such that a wavefront arriving from the cornea of the patient's eye obtains a reduction in said at least one aberration term provided by the cornea after passing said lens.

110. A multifocal intraocular lens according to claim 109, characterized in that the nonspheric surface of the lens is designed to reduce at least one positive aberration term of a passing wavefront.

111. A multifocal intraocular lens according to claim 109 or 110, characterized in that the at least one wavefront aberration term provided to the passing wavefront by the lens is a spherical aberration term, such that a wavefront arriving from the cornea of

the patient's eye obtains a reduction in said spherical aberration term provided by the cornea after passing said lens.

112. A multifocal intraocular lens according to any one of the claims 109 to 111, characterized in that the at least one wavefront aberration term provided to the passing wavefront by the lens is at least one term of a Zernike polynomial representing the wavefront aberration of the cornea.

113. A multifocal intraocular lens according to claim 112, characterized in that the at least one wavefront aberration term provided to the passing wavefront by the lens is the 11th normalized Zernike term of a wavefront aberration of the cornea.

114. A multifocal intraocular lens according to any one of the claims 105 - 113, characterized in that said selected group of people is a group of people belonging to a specific age interval.

115. A multifocal intraocular lens according to any one of the claims 105 - 114, characterized in that the lens is adapted to be used by a patient that has undergone corneal surgery and in that said selected group of people is a group of people who have undergone corneal surgery.

116. A multifocal intraocular lens according to any one of the claims 105 - 115, characterized in that said selected group of people is a group of people who will undergo a cataract surgical operation.

117. A multifocal intraocular lens according to claim 109 or 110 characterized in that the nonspheric surface is a modified conoid surface having a conical constant (cc) less than zero.

118. An multifocal intraocular according to claim 117 characterized in that it, for at least one of the foci, is capable of eliminating or substantially reducing spherical aberration of a wavefront in the eye or in an eye model arriving from a prolate surface

having the formula:

$$z = \frac{(\frac{1}{R})r^2}{1+\sqrt{1-(\frac{1}{R})^2(\mathbf{cc}+1)r^2}} + \mathbf{ad}r^4 + \mathbf{ae}r^6$$

the conical constant cc has a value ranging between --1 and 0,
R is the central corneal radius and
ad and ae are aspheric constants.

119. A multifocal intraocular lens according to any one of the claims 109 - 118, characterized in that one of the at least one nonspheric surface of the lens is the anterior surface.

120. A multifocal intraocular lens according to any one of the claims 109 - 118, characterized in that one of the at least one nonspheric surface of the lens is the posterior surface.

121. A multifocal intraocular lens according to any of the claims 104 - 120, characterized in that the reduction of aberrations is optimized for one of the foci.

122. A multifocal intraocular lens according to claim 121, characterized in that the reduction of aberrations is optimized for the base focus.

123. A multifocal intraocular lens according to claim 121, characterized in that the reduction of aberrations is optimized for one of the at least one additional focus.

124. A multifocal intraocular lens according to any of the claims 104 to 120, characterized in that the reduction of aberrations is optimized for the base focus and the at least one additional focus, simultaneously.

125. A multifocal intraocular lens according to any of the claims 104 to 124, characterized in that it is of diffractive type.

126. A multifocal intraocular lens according to claim 125, characterized in that the diffractive pattern is formed on the anterior and/or posterior surface of the lens.

127. A multifocal intraocular lens according to claim 125, characterized in that the diffractive pattern is formed on the lens surface that is modelled to reduce aberrations of the optical system.

128. A multifocal intraocular lens according to claim 125, characterized in that the diffractive pattern is formed on one surface of the lens and the other surface of the lens is modelled to reduce aberrations of the optical system.

129. A multifocal intraocular lens according to any of the claims 104 to 124, characterized in that it is of refractive type with anular rings with different radii of curvatures.

130. A multifocal intraocular lens according to claim 129 characterized in that the anular rings are formed on the lens surface that is modelled to reduce aberrations of the optical system.

131. A multifocal intraocular lens according to claim 129 characterized in that the anular rings are formed on one surface of the lens and the other surface is modelled to reduce aberrations of the optical system.

132. A multifocal intraocular lens according to any of the claims 104 to 131, characterized in that it is bifocal.

133. A multifocal intraocular lens according to any one of the claims 104 to 132, characterized in that the lens is made from a soft biocompatible material.

134. A multifocal intraocular lens according to any one of the claims 104 to 133, characterized in that the lens is made of a silicone material.

135. A multifocal intraocular lens according to claim 134, characterized in that the silicone material is characterized by a refractive index larger than or equal to 1.43 at a wavelength of 546 nm, an elongation of at least 350 %, a tensile strength of at least 300 psi and a shore hardness of about 30 as measured with a Shore Type A Durometer.

136. A multifocal intraocular lens according to any one of the claims 104 to 133,, characterized in that the lens is made of hydrogel.

137. A multifocal intraocular lens according to any one of the claims 104 to 132,, characterized in that the lens is made of a rigid biocompatible material.

138. A multifocal intraocular lens according to any one of the claims 104 to 137,, characterized in that it is designed to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000698 mm to 0.000871 mm for a 3 mm aperture radius.

139. A multifocal intraocular lens according to any one of the claims 104 to 137, characterized in that it is designed to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000161 mm to 0.000200 mm for a 2 mm aperture radius.

140. A multifocal intraocular lens according to any one of the claims 104 to 137, characterized in that it is designed to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000465 mm to 0.000419 mm

for a 2,5 mm aperture radius.

141. A multifocal intraocular lens according to any one of the claims 104 to 137, characterized in that it is designed to balance the spherical aberration of a cornea that has a Zernike polynomial coefficient representing spherical aberration of the wavefront aberration with a value in the interval from 0.0000868 mm to 0.00163 mm for a 3,5 mm aperture radius.

142. A multifocal intraocular lens according to any one of the claims 104 to 141, characterized in that it is designed to provide substantially the same reduced aberrations for all foci.

143. A multifocal intraocular lens according to any one of the claims 104 to 142 characterized in that the sum of the modulation for the two or more foci is more than 0.40, at a spatial frequency of 50 cycles per millimetre, when measured performed in an average/individual eye model using a 5mm aperture.

144. A multifocal intraocular lens according to claim 143 characterized in that the sum of the modulation for the two or more foci is more than 0.50.

145. A multifocal intraocular lens according to claim 143 or 144, characterized in that it is bifocal with a light distribution of 50-50% between the two foci having a modulation of at least 0.2 for each focus.

146. A multifocal ophthalmic lens having at least one nonspherical surface which when expressed as a linear combination of polynomial terms representing its aberrations is capable of reducing similar such aberration terms obtained in a wavefront having passed the cornea, thereby obtaining an eye sufficiently free from aberrations.

147. A lens according to claim 146, wherein said nonspherical surface is the anterior surface of the lens.

148. A lens according to claim 146, wherein said nonspherical surface is the posterior surface of the lens.

149. A lens according to any one of the claims 146 to 148, being a multifocal intraocular lens.

150. A lens according to any one of the claims 146 to 149, wherein said polynomial terms are Zernike polynomials.

151. A lens according to claim 150 capable of reducing polynomial terms representing spherical aberrations and astigmatism.

152. A lens according to claim 151, capable of reducing the 11th Zernike polynomial term of the 4th order.

153. A lens according to any one of the claims 146 to 152 made from a soft biocompatible material.

154. A lens according to claim 153 made of silicone.

155. A lens according to claim 153 made of hydrogel.

156. A lens according any one of the claims 146 to 152 made of a rigid biocompatible material.

157. Multifocal intraocular lens according to any of the claims 104 to 131, characterized in that it is a bifocal intraocular lens of diffractive type with a nonspheric anterior surface, and a diffractive pattern formed on the posterior surface.

158. Multifocal intraocular lens according to claim 157 characterized in that it has a light distribution of 50-50% between the two foci.

159. Multifocal intraocular lens according to claim 157 characterized in that it has a light distribution of 60-40% between the two foci.

160. Multifocal intraocular lens according to claim 157 characterized in that it has a light distribution of 40-60% between the two foci.

ABSTRACT

A method of designing a multifocal ophthalmic lens with one base focus and at least one additional focus, capable of reducing aberrations of the eye for at least one of the foci after its implantation, comprising the steps of: (i) characterizing at least one corneal surface as a mathematical model; (ii) calculating the resulting aberrations of said corneal surface(s) by employing said mathematical model; (iii) modelling the multifocal ophthalmic lens such that a wavefront arriving from an optical system comprising said lens and said at least one corneal surface obtains reduced aberrations for at least one of the foci. There is also disclosed a method of selecting a multifocal intraocular lens, a method of designing a multifocal ophthalmic lens based on corneal data from a group of patients, and a multifocal ophthalmic lens.

(Fig. 2)

1/2

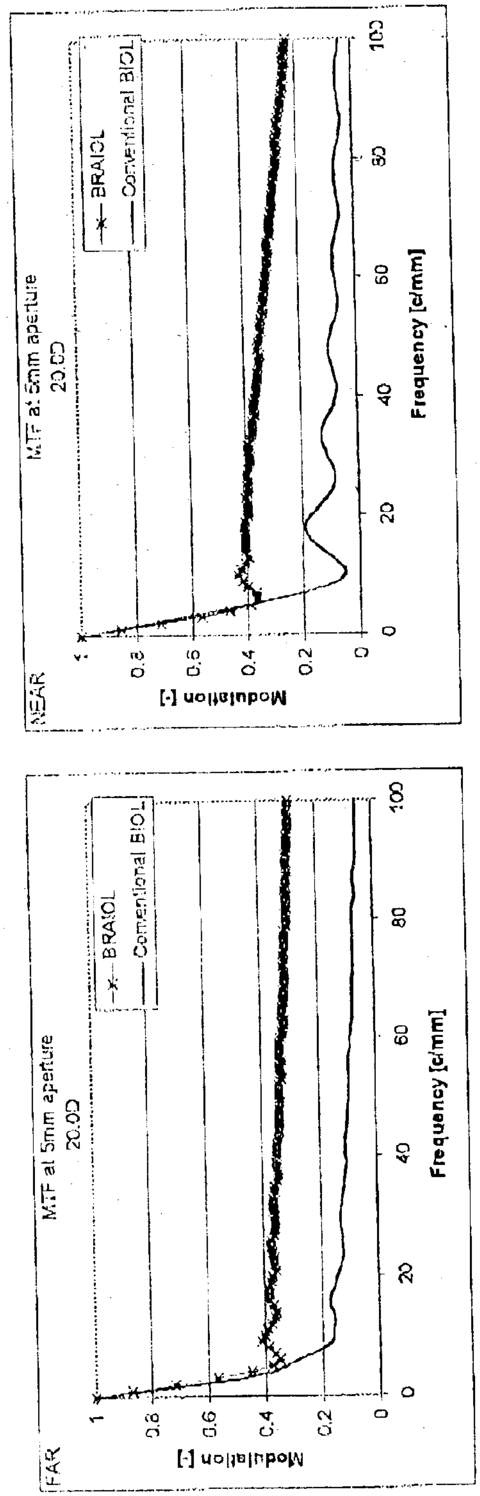
NEAR
MTF at 5mm aperture
20.0D
BRAIOL
Conventional BIOL
Modulation [-]
Frequency [c/mm]
FAR
MTF at 5mm aperture
20.0D
BRAIOL
Conventional BIOL
Modulation [-]
Frequency [c/mm]

Fig. 1

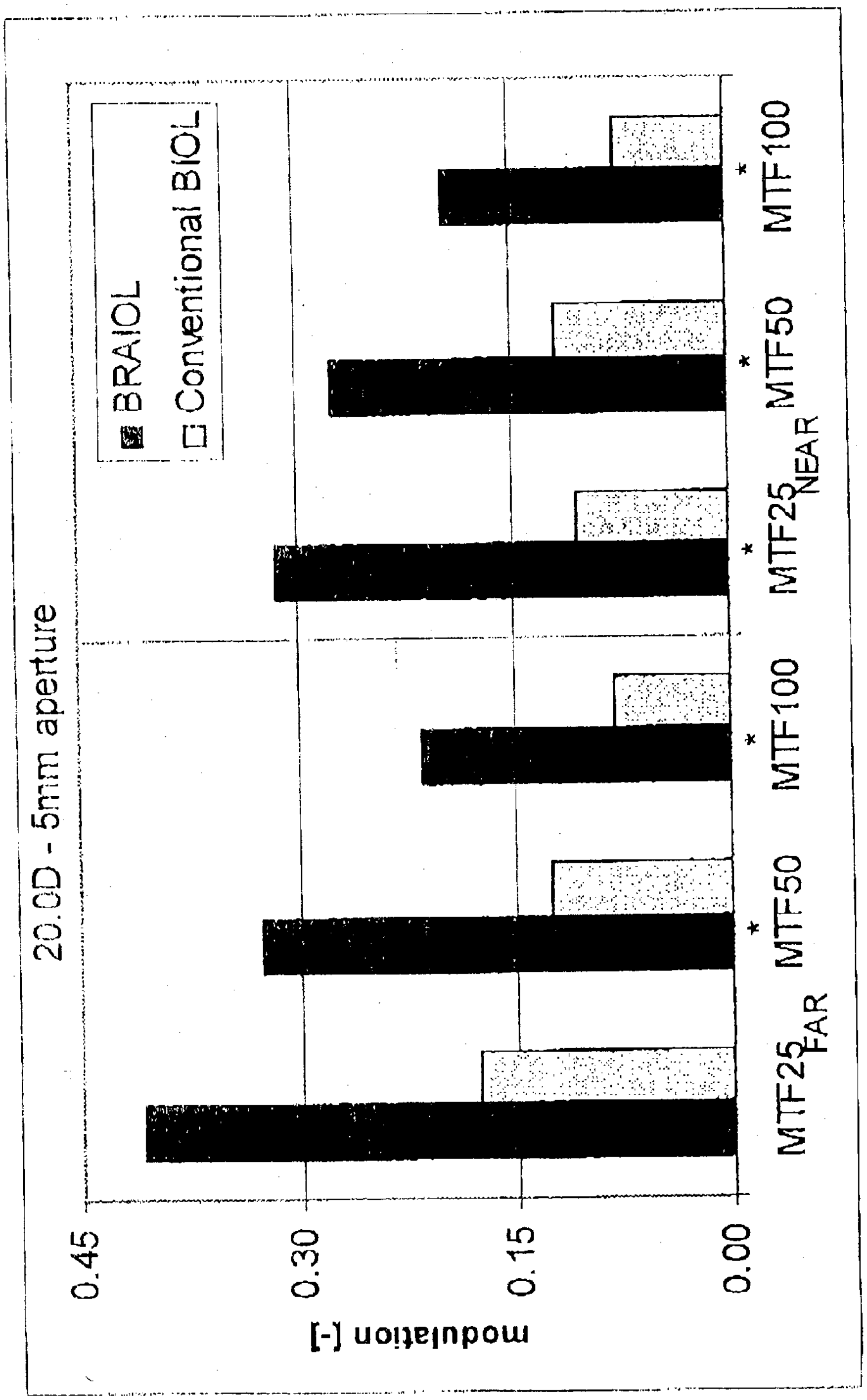
20.0D - 5mm aperture
BRAIOL
Conventional BIOL
modulation [-]
0.45
0.30
0.15
0.00
MTF25FAR
MTF50
MTF100
MTF25NEAR
MTF50
MTF100
*

Fig. 2